Field Testing of CFC-Free, Energy-Efficient Refrigerators in China

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Abstract

This article reports on the results of a year-long field test of prototype CFC-free, energy-efficient refrigerators developed during the Sino-US CFC-Free, Energy-Efficient Refrigerator Project. In early 1995, 104 refrigerators—85 prototypes and 19 baseline units—were installed in households in Beijing, Shanghai and Guangzhou. Watt-hour meters were installed to monitor energy usage, and the families were asked to respond to two questionnaires involving ownership and use of other appliances, satisfaction with the new and old refrigerators, rating of refrigerator characteristics, and other socio-economic information. Statistical analysis was performed on the energy consumption data along with the socio-economic information. Results show that laboratory measurements of prototype energy consumption closely match field energy consumption results in Shanghai, while energy consumption in Beijing and Guangzhou was lower for both the prototype and baseline models, with savings ranging from 22% in Beijing to 35% in Shanghai. Variables with important influence on energy consumption include model type, city, income level, and existence of kitchen fans and air conditioning. Except for noise levels, the prototypes generally received high consumer satisfaction ratings.

1. Introduction

The Sino-US CFC-Free, Energy-Efficient Refrigerator Project was initiated in 1989. The project was undertaken as part of a formal agreement between the China National Environmental Protection Agency (NEPA) and the US Environmental Protection Agency (USEPA) to reduce the usage of CFCs and improved the energy efficiency of domestic refrigerators within China. The initial stage of the project involved the development of a CFC-free, energy-efficient refrigerator design that has been thoroughly tested for reliability, performance and safety. This effort included the testing of a large number of models with different refrigerants and foam-blowing agents, advanced refrigeration cycles, thicker insulation, and other energy saving technologies.

The second stage of the project involved the conversion of a demonstration refrigerator production line at a factory to batch production of the prototype model developed in the first stage. This model included the following features selected from the many alternatives tested:

- Dual-evaporator, single-compressor vapor compression cycle with a valve directing the flow of the refrigerant through both evaporators or the freezer evaporator only
- Isobutane refrigerant
- Americold HC-77 1.43-COP high-efficiency compressor
- Ten percent larger wire-tube type freezer evaporator
- Wire-tube type condenser
- Cyclopentane-blown foam insulation, increased by 23 mm on the sides, back, and bottom, and 15 mm in the door
- Improved gasket

2. Field Testing

Field testing of the prototypes was crucial to demonstrating the safety and reliability of the CFC-free, energy-efficient prototype design. Moreover, it was important to determine how the energy savings of the

prototype in daily home use compared to the results of laboratory testing. Given multiple door openings throughout the day, food loads in the freezer and fresh-food compartments, and widely varying indoor temperatures throughout the year, energy consumption in actual household use would be expected to increase for both baseline and prototype units, reducing the relative savings. What is important to the future growth of electricity demand in China, however, is the potential for absolute savings relative to the baseline model.

The field testing program was designed initially to include all 200 of the manufactured prototypes, but about half the models were redirected before shipment to the three cities for testing. The field test period was set at one year, in order to capture the effect of all four seasons on refrigerator performance. Field testing took place in Beijing, Shanghai, and Guangzhou. The selected cities are large urban centers, with a substantial base of "middle class" consumers and about 100 percent refrigerator penetration in the urban market.

The three cities are indicative of three of China's major climate zones. Beijing, in North China, has a temperate climate characterized by hot wet summers and cold, dry winters. The annual average temperature is 12.9°C, with wide annual variations. The permanent population (i.e., excluding migrant workers) was 10.7 million at the end of 1995. Shanghai, at the mouth of the Yangzi River on the East China Sea, has a temperate climate characterized by hot wet summers and mild winters. The annual average temperature is 16.5°C, and the temperature usually remains above freezing during the winter. Shanghai is China's largest city, with population of 13.01 million at the end of 1995. Guangzhou, capital of the southern province of Guangdong, has a sub-tropical climate averaging 22.5°C in temperature annually. The summers are hot and wet, and winter warm. Guangzhou had 6.47 million inhabitants at the end of 1995. (SSB 1996)

3. Methodology

About 30 typical households were selected in each city to participate in the field test program out of a pool of about 60 households per city identified as possible participants. Participants were offered a prototype or baseline model refrigerator at a substantial discount to the market price. In addition, the households were offered regular payments during each stage of the program. All field test units were placed in the same part of each city to facilitate data collection.

In May and June, 1995, a total of 85 CFC-free, energy-efficient prototype units—model BCD-222B—and 19 baseline units—model BCD-225—were installed in the participating households. Incomplete energy consumption data were collected for four prototypes and five baseline units in Guangzhou. In addition, one prototype refrigerator failed and was dropped from the field test in Shanghai. Table 1 shows the locations of the remaining 94 field test units and the dates over which energy consumption readings were made.

At the time of the refrigerator installation, a watt-hour meter was also installed on all units to monitor energy usage. Readings of cumulative power consumption were made weekly for two months, and then monthly for the remainder of the roughly year-long field test program. A questionnaire designed to gather relevant socio-economic data such as household size, income, ownership of other appliances and usage patterns was administered one month into the test period. In addition, a second questionnaire concerning the customer's opinion about the prototype refrigerator was given at the end of the test period.

4. Characterization of Study Households

As part of the study, data were collected on the study households, old refrigerators, ownership and use of other appliances, and how households used their new refrigerators. These data were collected through

Table 1. Locations and Dates of Field Tests

City	Number of Units in Test	Test Dates
Beijing		
Prototype units	27	7/2/95 to 6/29/96
Baseline units	7	7/2/95 to 6/29/96
Guangzhou		
Prototype units	18	7/5/95 to 1/22/96
Baseline units	2	7/5/95 to 1/22/96
Shanghai		
Prototype units	35	6/25/95 to 6/20/96
Baseline units	5	6/25/95 to 6/20/96

questionnaires administered near the beginning and end of the study period to better understand household characteristics and how variations in household characteristics may affect refrigerator energy use.

Study Households

Households in the study had an average size of 3.1 people, with the average slightly higher in Beijing and slightly lower in Shanghai and Guangzhou. For China's urban areas as a whole, the average household size was 3.23 in 1995, down slightly from 3.28 in 1994 (SSB 1996).

Nearly half the households in our study has a monthly income as of mid-1995 between RMB 1001-1500 (about US$120-180), with about one-quarter having lower incomes and one-quarter having larger incomes. This income level of half of the respondents places them within the range of medium and medium-to-high income levels in urban areas (third and fourth quintiles). In 1995, the average monthly income per household in China's largest cities reached RMB 1407 (about US$170).

Old Refrigerators

All of the households in the study already owned refrigerators. Nearly all of these refrigerators were smaller than the new prototype model, averaging 165 liters (Table 2). The original units ranged in age from 2 to 20 years old, with the average unit being approximately eight years old, according to verbal reports by a member of each household. On average, the old refrigerator consumed 1.14 kWh/day, according to standardized testing information on the refrigerator nameplate. This is 36 percent more than the laboratory-tested consumption of the new prototype model. Thus, assuming these label measurements accurately portray consumption in the field, the average household could expect their new refrigerator to use 26 percent less energy than their previous unit. Old refrigerators were produced by more than a dozen

Table 2. Information on Old Refrigerators

Item	Average	Range	Number of Responses
Old refrigerator size	165 liters	100-220	41
Old refrigerator energy use	1.14 kWh/day	0.5-1.6	35
Year old refrigerator purchased	1987	1975-1993	40

manufacturers, with the largest number (nearly 30%) produced by Beijing-based Snowflake, formerly China's largest refrigerator manufacturer.

Ownership and Use of Other Appliances

Each of the households surveyed owned many types of appliances. Nearly all households had televisions and fans, and many had more than one. Around 70 percent of the households also owned clothes washers and microwave ovens. For the most part, ownership patterns are broadly consistent among cities, with the exception of space conditioning equipment. One-third of study households in Shanghai and Guangzhou owned air conditioners, while only 6 percent did in Beijing. Likewise, more than half of Shanghai households owned electric space heaters, because many apartments lack central heat despite average winter temperatures of approximately 6°C (43°F). In Guangzhou the climate is too warm generally to need space heating, while in Beijing all apartments have central heating.

As part of the survey, data were also collected on appliance nameplate power use and resident estimates of annual operating hours (broken down into days used per year and hours per day). Nameplate power use is typically a maximum load—average use is often substantially lower. Household estimates of operating hours are probably not very accurate. Also, for some of the appliances and cities, sample sizes were small and thus averages are biased by outliers. These data are summarized in Table 3. Particularly notable is the fact that residents report that on average televisions are operated 1235 hours per year, or over 3 hours per day on average.

Table 3. Information on Appliance Ownership and Operations in Study Households

Equipment Type	% of Households Possessing	Average Power (Watts)	Average Hours Used Per Year
Air conditioner	B: 6% S: 34% G: 33% Total: 24%	B: 800 S: 1172 G: 901 Total: 1040	B: 315 S: 328 G: 183 Total: 286
Washing machine	B: 73% S: 70% G: 63% Total: 69%	Total: 346	B: 123 S: 152 G: 199 Total: 159
Electric space heater	B: 3% S: 56% G: 0% Total: 22%	Total: 929	B: NA S: 259
Fan	B: 153% S: 143% G: 131% Total: 143%	Total: 103	B: 209 S: 426 G: 519 Total: 402

Equipment Type	% of Households Possessing	Average Power (Watts)	Average Hours Used Per Year
Rice cooker	B: 39% S: 52% G: 44% Total: 45%	Total: 659	Total: 343
Microwave oven	B: 70% S: 69% G: 56% Total: 65%	Total: 105	Total: 520
Kitchen exhaust fan	B: 12% S: 31% G: 0% Total: 16%	Total: 737	Total: 580
Television	B: 138% S: 124% G: 81% Total: 117%	Total: 103	Total: 1235

Note: B= Beijing; S=Shanghai; G=Guangzhou; Total = total of all three cities. Where individual values are not provided, values for individual cities were very similar to each other or sample sizes for individual cities were too small to be meaningful. Values greater than 100% indicate ownership of multiple units in households. Guangzhou data are derived from a small sample and may be biased. Guangzhou TV ownership may be biased downward, since no Guangzhou respondent answered the survey question about ownership of a second television.

Use of New Refrigerators

One month after the new refrigerator was installed, field staff visited each apartment and measured temperatures in the fresh food and freezer compartments using a mercury bulb thermometer. On average, they found that freezers were -17°C (+1°F) and fresh food compartments were 9°C (48°F). While Beijing temperatures were lower, temperature measurements were only made in a few Beijing homes, and thus these differences may not be significant. On average, both the fresh food and freezer compartments were approximately half full with food at the time of the field visit.

5. Field Test Energy Consumption Results

On completion of the field tests in June 1996, energy consumption results were compiled and combined with socio-economic data into one large data set, and a series of analyses of variance were performed. The results of these analyses are described below. The analyses were based on 85 observations of energy consumption with associated socio-economic information, since 9 more observations—one prototype in Beijing, one baseline in Guangzhou, and seven prototypes in Shanghai—contained more than 90 percent missing values and had to be deleted from the analyses. All analyses were performed with Statistical Analysis System (SAS) procedures Proc Ttest and Proc Glm.

Overall Energy Consumption

The two-sample t-test revealed that prototype refrigerators consumed on average 26.8 percent less energy than baseline refrigerators. This difference is significant, with the p-value less than .0001. This p-value indicates that there is only a .01 percent chance that the average energy consumption of the prototype re-

frigerators is the same as that of the baseline refrigerators. The 95 percent confidence interval for the energy savings of the prototypes is 21.5 to 32 percent.

Laboratory tests of the prototype model BCD-222B showed an average 39 percent reduction in energy use compared to the baseline BCD-220 model. Based on Chinese testing procedures (performed at an ambient temperature of 25 °C), the BCD-222B consumed 0.84 kWh per day, compared to 1.37 kWh per day for the BCD-220 model. The BCD-220 was, however, replaced by a new BCD-225 model at the time of the field testing program. About 5 percent more efficient than the 220, the 225 consumed 1.3 kWh per day (based on Chinese testing standards). With the BCD-225 as the baseline model, the prototype thus consumed 35% less energy in standard tests (Table 5).

Table 5. Mean Energy Consumption, kWh/day

Model	City	Mean	Sample Size
Prototype	Beijing	0.78	26
Prototype	Guangzhou	0.79	18
Prototype	Shanghai	0.84	28
Baseline	Beijing	1.00	7
Baseline	Guangzhou	1.10	1
Baseline	Shanghai	1.29	5

Relationship of Energy Consumption to Socio-Economic Factors

This analysis seeks to determine if the observed difference between the energy consumption of the prototypes and baselines can be explained by any of the socio-economic factors collected in the questionnaire. For example, if all prototype refrigerators happened to be installed in Beijing and all baseline models in Guangzhou, the difference in energy consumption could simply be due to the difference in temperature between the cities. Hence it is reasonable to examine the differences between models by city, income group, and other factors. Results for some of these pair-wise comparisons of prototypes and baselines are summarized in Tables 6 through 10.

Table 6. Energy Savings versus Location
n=85

City	Energy Savings	p-value	Conclusion	95% Confidence Interval for Energy Savings
Beijing	22%	.0001	Significant	(18.5%, 25.5%)
Guangzhou	28%	.0003	Significant	(20.8%, 35.3%)
Shanghai	34.7%	.0001	Significant	(32.1%, 37.2%)

Table 7. Energy Savings versus Family Income
n=84

Income Group	Energy Savings	p-value	Conclusion	95% Confidence Interval for Energy Savings
2	28.5%	.1203	Non-significant	
3	32.6%	.0009	Significant	(26.8%, 38.4%)
4	18.1%	.0001	Significant	(12.1%, 24.1%)
5	36.5%	.0001	Significant	

Table 8. Energy Savings versus Air Conditioning
n=84

A/C	Energy Savings	p-value	Conclusion	95% Confidence Interval for Energy Savings
No	24.7%	.0006	Significant	(17.7%, 31.7%)
Yes	30.6%	.0001	Significant	(24.7%, 36.5%)

Table 9. Energy Savings versus Electric Space Heater
n=84

Heater	Energy Savings	p-value	Conclusion	95% Confidence Interval for Energy Savings
No	25.5%	.0001	Significant	(19.8%, 31.3%)
Yes	34.0%	.0001	Significant	(29.7%, 38.3%)

Table 10. Energy Savings versus One Fan
n=80

One Fan	Energy Savings	p-value	Conclusion	95% Confidence Interval for Energy Savings
No	21.4%	.0009	Significant	
Yes	27.1%	.0001	Significant	(21.4%, 32.7%)

Table 6 indicates that geographical location is a significant indicator of prototype energy savings. The results shown in Tables 7 to 10 indicate that the prototype's energy savings is significant for these other variables as well. This implies that the observed difference in energy consumption can be explained by no single variable, other than that the prototype is more energy efficient than the baseline. (An insufficient number of complete data sets was available to do a step-wise analysis to determine if the energy consumption difference between the two models could be explained by a combination of two or more of the socio-economic factors.)

Tables 7 to 10 compared the energy consumption of the two models as a function of one of the socio-economic factors (e.g. city, family income, etc). The energy consumption of the baseline and prototype models in these comparisons was in most cases significantly different. It is also possible to look at one model and determine if its energy consumption is significantly affected by socio-economic factors. For example, looking separately at apartments with and without air conditioning, it can be ascertained if energy consumption of the prototypes and baseline models is significantly influenced by the presence of air conditioning. The result of this analysis shows that except for city temperature, the relationships between prototype energy consumption and the various socio-economic factors are not significant. Additionally, except for family income and number of inhabitants, the relationships for the baseline units are all significant. Thus the energy consumption of both refrigerators is strongly dependent on city temperature and independent of family income or family size.

Finally, an analysis for "important" variables affecting the energy consumption of all of the refrigerators indicates that the factors given in Table 11 have a significant effect on energy consumption:

Table 11. "Important" Variables Affecting Prototype Energy Consumption

Factor	p-value	Number of Observations Used in Analysis
Model type	.0001	85
City	.0001	85
Income	.0014	84
Kitchen fan	.0019	83
Air conditioning	.0035	84
Number of people	.0105	36
Two fans	.0480	80

It must however be noted that the significance of the effect of number of people in household on energy consumption is not as reliable as the other conclusions because the analysis is based on too few (i.e., 36) observations. Also, the p-value for ✌Two Fans✍ is close to .05, so this factor is likely insignificant.

Summary of Findings

Despite the limited size of the data set collected by the end of the field test period, several conclusions can be drawn about the operation of the prototype refrigerator in households. Clearly, the prototype refrigerator demonstrated substantial energy savings over the baseline model, averaging a reduction of 27 percent in power consumption. This compares to a 35 percent reduction in laboratory testing.

Greater savings were enjoyed in the warmer cities, with the lowest savings found in Beijing (22%) and the highest in Shanghai (35%). The lower savings in Beijing and Guangzhou were in part due to the unexpectedly low electricity use of the baseline refrigerators, which consumed on average 19 percent less power than in laboratory tests. Power use by the prototype refrigerators in these two cities also was about 7 percent less than in laboratory tests. In both cases, relative and absolute savings were lower than what was achieved in the laboratory. Interestingly, the consumption figures for Shanghai almost exactly matched laboratory tests for both the prototype and the baseline, resulting in comparable savings.

Households with space heaters showed higher energy savings than those without space heaters, as would be expected from refrigerators with thicker insulation. Some results, however, were counterintuitive, as higher savings were also demonstrated in households with air conditioners and kitchen exhaust fans.

Households with air conditioners achieved an average 34 percent reduction in refrigerator energy consumption compared to 26 percent for non air-conditioned households. Kitchen exhaust fans, which would also presumably reduce kitchen temperatures, also affected savings: in those households equipped with kitchen exhaust fans, savings increased by 6 percent.

Shanghai had the highest level of space heater ownership. The heaviest use of air conditioners was also in Shanghai, where both the power rating and number of hours of annual use were higher than in Beijing and Guangzhou (see Table 3). Shanghai led in terms of the number of households with kitchen exhaust fans, and the higher ownership of all three types of appliances may in some way explain the greater savings achieved there.

Further analysis and explanation of the savings in the prototype refrigerator is not possible owing to the absence of data on such potential causative factors as door opening and room temperatures.

6. Consumer Reaction Analysis

By examining factors that consumers like and dislike, manufacturers can improve product design and make the product more appealing. This information is also useful to discover how to best promote a new product, or to promote existing products in new markets. These were the reasons underlying the development of a consumer opinion portion of the household survey questionnaire. This section summarizes consumer reactions to the 85 prototype units that were placed in the three cities for field testing.

Satisfaction Ratings

Participating households were asked to list their top two likes and dislikes about the prototype. Households were given a list of ten features from which to choose, and an opportunity to add features of their own selection to the list.

When participating households were asked what they liked most about the prototype, 62% of responses listed storage capacity. The new model, at 222 liters, provided 35 percent more space than the average of the refrigerators replaced (the increase ranged from 0% to 122%). Additional factors rated as highly desirable include the prototype's styling and temperature reliability. While few households listed the prototype's beneficial environmental impact as one of the primary desirable features, a significant number of households listed this feature as their second (29 out of a total of 98 second-choice responses) choice, making this the second most highly ranked feature overall. Relatively few households listed the prototype's energy efficiency as a desirable feature, even though over two-thirds of the households reported lower energy consumption after installation of the prototype

Three features were highlighted by households as unsatisfactory. The most disliked feature (39 of 86 responses, or 45%) was noisy operation. Notably, 38 of a total of 65 respondents (58%) listed this as their first selection regarding the prototype's most unsatisfactory feature. The feature listed next most often as unsatisfactory was the lack of an automatic defrost system (23%), followed by unattractive styling (16%). Also notable is that more respondents listed unattractive styling as their first most unattractive feature than listed lack of an automatic defrost system (11 versus 7 respectively). However, none of the households that responded to this question found the new model a poor value for the money. It is also interesting to note that there were significantly more 'likes' than 'dislikes' listed (218 versus 86) in evaluation of the prototype.

Energy Use

Participating households were asked if they noticed a difference in their electricity usage since installation of the prototype. Of those that reported seeing a difference, 68% reported that they used less electricity after installation of the prototype. For those households which made information available on the rated

power consumption of their previous unit, the decrease in average rated refrigerator electricity use for households reporting less energy use was 0.62 kWh/day, in comparison to 0.41 kWh/day for households which reported an increase in energy use. Households which reported a decrease in energy use had average prototype energy consumption of 0.72 kWh/day, as opposed to 0.85 kWh/day (18% higher) for households which reported noticing an increase in energy use. Those households that reported noticing an increase in their energy use had, on average, relatively smaller models of the old refrigerators that consumed less electricity (the average of all old models was 1.14 kWh/day). The savings from the prototype, therefore, were correspondingly less, and may have been compensated for by an increase in other electricity use.

7. Conclusions

The field testing of the prototype refrigerator demonstrated the technical feasibility of manufacturing a CFC-free, energy-efficient refrigerator for household use. The results of the year-long field test showed that the prototype saves energy—from 22% to 35% depending on location. The savings were, however, slightly less than expected. It is unclear if the lower savings were due to the small number of baseline units in the field or if other factors were present for which data are lacking for analysis.

Among the factors found to have a significant impact on energy consumption of the models were the model type (baseline vs. prototype), location (city), family income, and the presence or absence of air conditioning and a kitchen fan. The limited sample size made it difficult to determine which factors, or combination of factors, played a significant role in influencing energy consumption.

Consumers in general liked the prototype refrigerator and indicated that they would recommend it to their friends. The storage capacity of the refrigerator—in many cases larger than the refrigerator it replaced—was considered its most desirable feature, and consumers felt that the refrigerator performed well in maintaining food at the desired temperature. Significantly, environmental protection was an important factor contributing to consumer satisfaction with the refrigerator. A number of users had concerns about the noise level of the new refrigerator, the lack of an automatic defrost feature, and some felt that the styling was not adequate.

About one-third of households felt that energy consumption increased after installation of the prototype. This response is attributed at least in part to the increase in absolute refrigerator size for most consumers, and may also have been influenced by climate, indoor conditions, and other operating factors. It could also reflect that refrigerator savings were swamped by increased electricity use by other appliances or lighting at the same time.

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